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CMS Physics Analysis Summary

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Jet Corrections to Parent Parton Energy

The CMS Collaboration

Abstract

Jet production in hadron collisions results from the hard scattering of partons. The outgoing partons, which cannot be directly observed because of color confinement, produce jets of particles which can be detected. CMS will correct the measured jet energy for instrumental effects. In addition, some measurements can benefit from further corrections which connect on average the p_T of a jet to the p_T of the associated parton in the hard scattering. This is a correction for theoretical effects which has been computed at the generator level with a Monte Carlo simulation. This parton level correction depends on the flavour of the jet and the physics process being simulated. Here we describe the parton level correction which has been implemented at CMS.

1 Introduction

The CMS detector [1] provides a direct measurement of the energy for hadrons, photons and leptons. The raw energy deposited in the calorimeter can be clustered, using different algorithms [2], to produce jets. The jet energy, obtained by summing up the selected components of the jet, is affected by a series of instrumental and theoretical "effects" and a correction procedure is needed to recover on average the original value. Moreover, different physics measurements could require different levels of correction. CMS has adopted a modular procedure where the jet energy correction is factorized into several sub-corrections. For a detailed description of the full correction procedure see reference [3]. Here we describe the parton level correction, which is the final sub-correction in that chain.

The aim of this note is to describe in detail the procedure adopted to evaluate from Monte Carlo the parton level jet correction. This correction connects on average the particle jet p_T to the parton p_T in the hard scattering. A first attempt to calculate this effect was already done in CMS [4] and the approach chosen for this work is similar. The basic idea is to match all the partons in the final state obtained from a matrix element generator to the particle level jets to evaluate on average the effect of the showering/hadronization and jet algorithm. This study uses a lowest order (LO) QCD generator, but the same procedure can be applied in principle to a next to lowest order (NLO) or higher order calculation. The validity of this approach ends when the connection of the particle jet to the parton in the hard scattering is no longer approximately one to one. For example, a boosted W boson or a boosted top quark would result in a final state with 2 or more collinear partons. Our correction does not cover such cases.

The parton level jet correction is an optional correction which could help when measured quantities are compared to theoretical values for some measurements. In particular when an invariant mass of a known particle decaying into partons is reconstructed from two or more jets and compared to the known value. For example, a hadronically decaying top quark. Using jets corrected up to the parton level should give a reconstructed mass that is closer to the true particle mass, particularly when the jets are soft.

The parton level jet correction depends on the theoretical model of the event. It depends mainly on the generator used, the parameters for the underlying event, the multiple parton interactions, the parton density functions (PDFs), the flavour of the jet and the process considered. It also depends on the choice of jet algorithm chosen by the experiment. Here we present a set of correction functions for different choices of theory parameters and jet algorithms. The corrections are determined separately for di-jet events and $t\bar{t}$ events to explore the process dependence of the correction. We also present some initial estimates of the systematic uncertainty.

2 General Procedure and Data Samples

The basic starting point to extract the correction function is to calculate the generator response defined as the ratio between a particle level jet p_T and the associated parton p_T. The particle level jet (or *GenJet* in the following) is reconstructed using all the stable particles (as defined by Pythia [5]) in the generated event. The jet clustering algorithms considered in this study are:

- Iterative Cone Algorithm $\Delta R = 0.5$ (IC5);
- k_T Algorithm with $D = 0.4$ and $D = 0.6$ (KT4 and KT6 respectively);
- SisCone Algorithm with $\Delta R = 0.5$ and $\Delta R = 0.7$ (SC5 and SC7 respectively).

All the jets matched to a hard scattered parton are used for the generator response calculation. An accepted match is defined using the $\Delta R = \sqrt{\Delta\phi^2 + \Delta\eta^2}$ metric in the $\eta - \phi$ plane. Different values of ΔR_{match} have been investigated going from 0.05 up to 0.30. One-to-One matching is used to avoid the same parton matched to more than one jet.

Different responses defined as the most probable value (MPV) of the ratio p_T^{jet}/p_T^{parton} distribution are calculated for different jet flavours. The jet flavour is defined as the flavour of the matched parton. Each matched jet is therefore labeled as a gluon jet, a light quark jet (*uds*), a charm quark (*c*) jet or a bottom quark (*b*) jet.

The generator response is calculated also for the full set of matched jets without any flavour identification. Such a quantity is clearly strongly process dependent because of the possible different mixture of light/heavy quark and gluon jets in the final state.

The physics processes studied are the $2 \rightarrow 2$ QCD di-jet and $t\bar{t}$ production. The events are generated using Pythia [5] Monte Carlo with DWT tuning [6] for the multiple-parton interactions and underlying events.

To understand the effect of different generators/tunings, events were also produced using the D6T [7] and S0 [8] tuning as well as using a different generator (Herwig [9] + Jimmy [10] for the multi-parton interaction, labeled as HRW in the following). Observed differences in the response were used to derive systematic uncertainties due to PDFs, underlying events, multi-parton interactions, and shower/fragmentation models.

2.1 The generator response

We need the correction for the particle level jets as a function of their transverse momentum p_T^{jet} and pseudo-rapidity η. However, when the response is measured in a bin of p_T^{jet}, the rapidly falling p_T^{parton} spectrum and the parton to jet resolution function introduces a bias in the response. This bias comes from the asymmetric migration or smearing of partons among the different p_T^{jet} bins. To avoid this bias, it is preferable to express the response function in term of p_T^{parton}, where this problem is absent, and then invert the response to obtain the correction for the particle jet.

The full (p_T,η) bi-dimensional space was therefore bin-mapped up to $|\eta| < 5$ and $p_T^{parton} < 1$ TeV/c. The response for each bin was defined as the most probable value of the $p_T^{GenJet}/p_T^{parton}$ ratio distribution obtained through a Gaussian fit. An example is shown in Fig. 1 and Fig. 2 respectively for light quark jets with $32 < p_T^{parton} < 36$ GeV/c and $872 < p_T^{parton} < 876$ GeV/c. Both the distributions are clearly non symmetric and sizable tails are frequently present for different jet algorithms and p_T regions. For low p_T bins, tails in the high response region, where the response is higher than one, depend on the relatively high contamination from underlying events. Conversely, high p_T bins show tails in the low response region of the distribution associated with final state radiation and hadronization effects, while the underlying events contamination is negligible. As a result of these tails the peak position of the distribution, the most probable value, is quite different from the mean.

Fig. 3 shows the gluon jets MPV of the $p_T^{GenJet}/p_T^{parton}$ distribution for a fixed η-ring as a function of p_T^{parton} for all the jet algorithms listed. As expected the IC5, SC5 and KT4 algorithms group together giving similar responses, while SC7 and KT6, with a bigger opening parameter, are well separated from the previous group. This is particularly evident in the low p_T range, while above ≈ 250 GeV/c this difference disappears. Similar plots were produced as a function of η

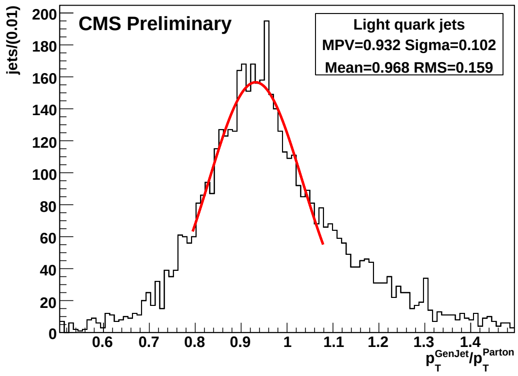

Figure 1: Parton-jet response $p_T^{GenJet}/p_T^{parton}$ distribution for light quark jets with $0.3 < |\eta| < 0.4$ and 32 GeV/c$< p_T^{parton} <$36 GeV/c. (IC5, ΔR_{match}=0.10, DWT)

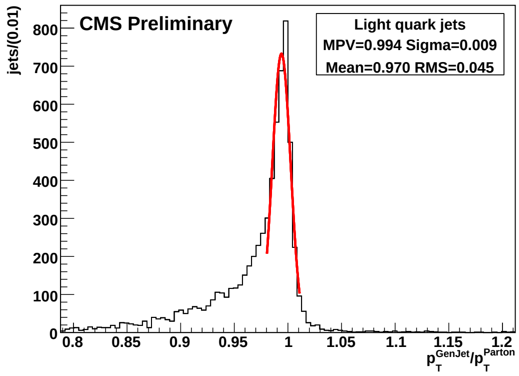

Figure 2: Parton-jet response $p_T^{GenJet}/p_T^{parton}$ distribution for light quark jets with $0.3 < |\eta| < 0.4$ and 872 GeV/c$< p_T^{parton} <$ 876 GeV/c. (IC5, ΔR_{match}=0.10, DWT)

for fixed p_T bins and the response dependence on η was found to be very mild (within ≈1% for the full η region). Fig. 4 shows the response for different jet flavours. Finally Fig. 5 shows how the choice of generator/tuning affects the response for gluon jets. DWT and D6T give the same response to within 1%, indicating that using CTEQ5L or CTEQ6L1 is not introducing a relevant change in the parton correction. The S0 tune gives a response higher than the default tune used in CMS particularly in the low p_T range, while the one obtained from Herwig+Jimmy is ≈2% lower for all the jet flavours over the whole p_T spectrum.

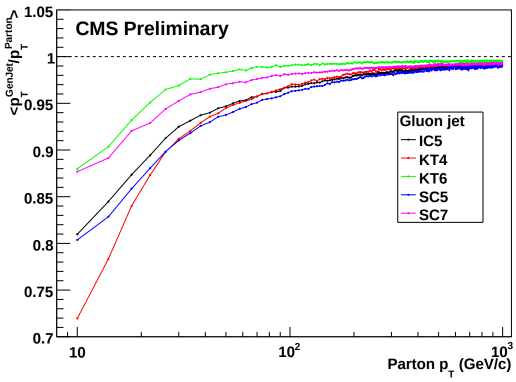

Figure 3: Parton-jet response for different jet algorithms (gluon jets, $0.3 < |\eta| < 0.4$, ΔR_{match}=0.10, DWT)

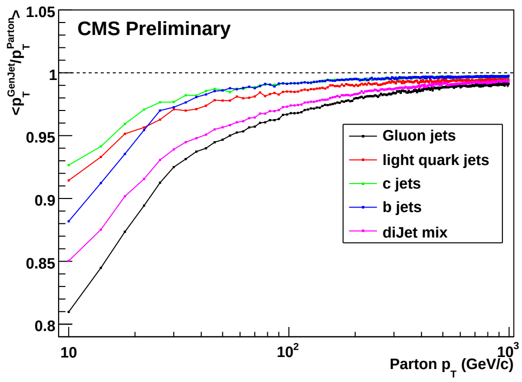

Figure 4: Parton-jet response for different jet flavours (IC5, $0.3 < |\eta| < 0.4$, ΔR_{match}=0.10, DWT)

3 The Response Distribution and the Correction Factor

The main goal of this work is the extraction of a global response function from the whole set of response distributions. The global function will depend on the jet reconstruction algorithm, the jet flavour, the jet η and p_T. The default tuning is DWT and ΔR_{match} = 0.10 is the chosen parton-jet matching parameter. Variations in the response due to different matching/tuning will be considered as sources of systematic uncertainty. The correction factor is defined from the global response function as:

$$C_{a,f}(\eta, p_T) = \frac{1}{R_{a,f}(\eta, p_T)} \tag{1}$$

where R is the global fitted response function. The index (a, f) indicates different jet algorithms and flavours. The global response fitting function depends on 8 parameters and was found empirically after a detailed study of the different response distributions and it is defined as:

$$\begin{aligned} R(\eta, p_T) &= a(p_T)|\eta|^2 + b(p_T)|\eta| + c(p_T) \\ a(p_T) &= a_0 + a_1 p_T \\ b(p_T) &= b_0 + b_1 \log p_T + b_2 \log^2 p_T \\ c(p_T) &= \frac{1}{c_0 + c_1 p_T} + c_2 \end{aligned} \tag{2}$$

It is calculated as a function of the parton p_T while to apply the correction to the reconstructed jets in the general CMS correction procedure, the particle jet p_T has to be used as input. The analytical inversion of the response function is not feasible because of its complexity and a numerical solution using a binary tree search was implemented.

4 The Closure Test

The main cross-check, or closure test, to evaluate the quality of the correction procedure just described is to use the corrected particle jets and calculate the most probable value of the $p_T^{corr.jets}/p_T^{parton}$ distribution as a function of p_T^{parton}. Any sizable difference from 1 would represent a systematic error in the correction procedure. Fig. 6 shows the peak position for the full set of corrected jets as a function of the p_T^{parton} when the matching ΔR_{match} is again fixed to 0.10 for the five jet clustering algorithms and all the considered flavours. Above p_T= 25 GeV/c all the 25 combinations algorithm/flavour are within 0.5% of 1 showing that the correction is working well. The correction however starts to become less precise at 20 GeV/c and the difference can be as big as 5% below 15 GeV/c; this is due to the global fitting function which fails to reproduce correctly the peak of the response distribution for such soft jets.

5 Parton correction and top events

Here we begin to explore the process dependence of the parton level correction. The global fitting function derived in this work was calculated from di-jet QCD events and it works correctly for that category of events. A legitimate question is whether or not this correction is general enough for other processes. A first attempt to verify the universality of the derived correction was made by comparing the parton-jet response obtained from di-jet and $t\bar{t}$ events. Fig. 7 shows clearly that the response is different for the two processes.

The difference between the parton level corrections for the di-jet and $t\bar{t}$ process is quite large. This is particularly true for the all jets mixture, due to the different amounts of gluon jets in di-jet and $t\bar{t}$ events. At the LHC energy most di-jet events have at least one gluon jet coming from

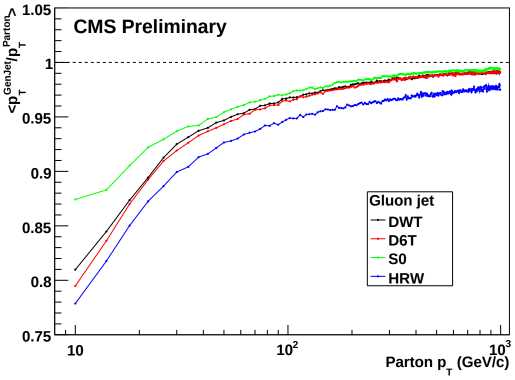

Figure 5: Parton-jet response for different generator tuning (gluon jets, IC5, $0.3 < |\eta| < 0.4$, ΔR_{match}=0.10)

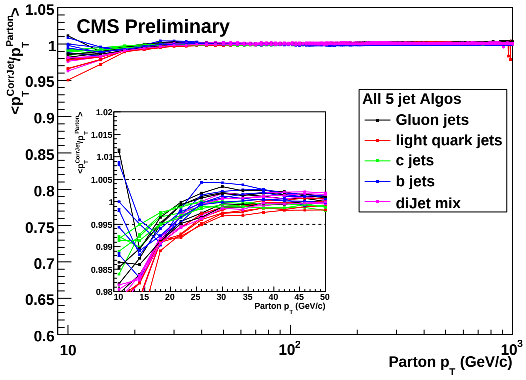

Figure 6: Closure test for di-jet events: Distribution for all the 25 algorithm/flavour combinations of $p_T^{corr.jets}/p_T^{parton}$ as a function of p_T^{parton} corrected using the global fitting function derived from di-jet events

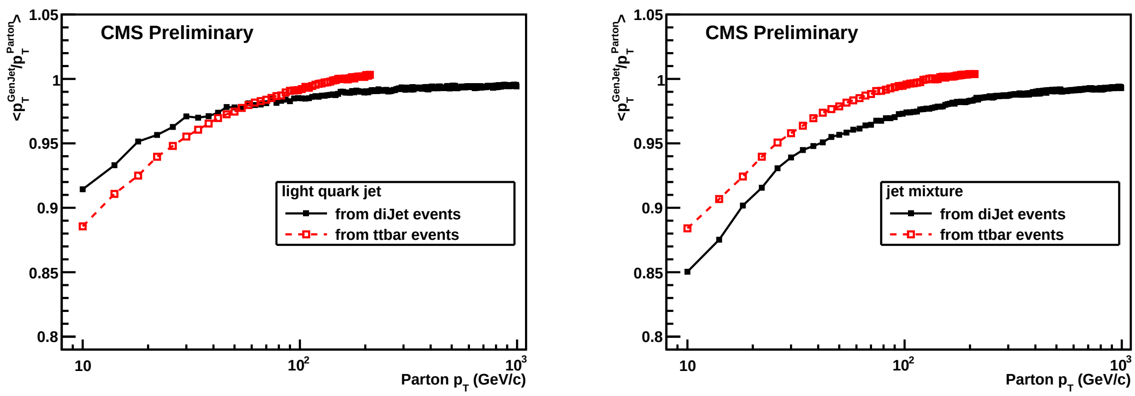

Figure 7: Comparison of the parton-jet response for $0.3 < |\eta| < 0.4$ obtained for di-jet events and $t\bar{t}$ events. Light quark jets on the left and mixture on the right (IC5, ΔR_{match}=0.10, DWT)

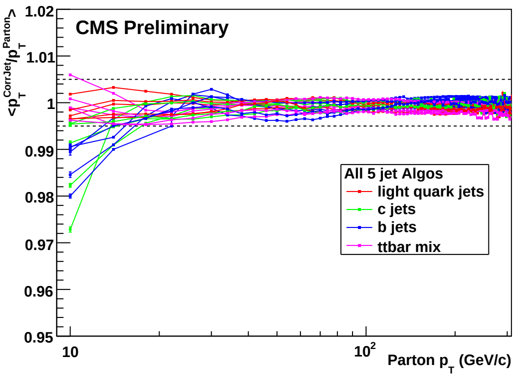

Figure 8: Closure test for $t\bar{t}$ events: Distribution for all the 20 algorithm/flavour combinations (no gluon jets in $t\bar{t}$ events) of $p_T^{corr.jets}/p_T^{parton}$ as a function of p_T^{parton} corrected using the global fitting function derived from $t\bar{t}$ events

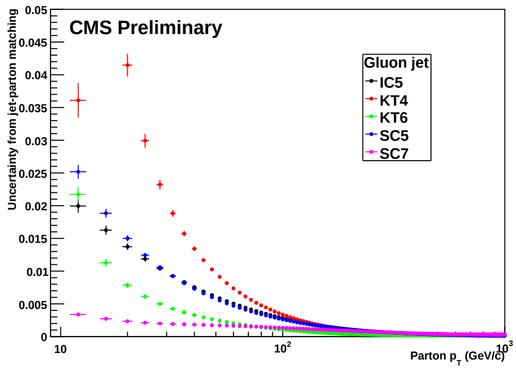

Figure 9: Comparison of the parton-jet response for different ΔR matching with respect to the default choice (ΔR=0.10): profile histogram of the absolute difference for the full η range (ΔR from 0.05 up to 0.30). All the 5 jet algorithms are reported (IC5, KT4, KT6, SC5 and SC7) and DWT tune

the hard scattering, while in $t\bar{t}$ events there are no gluon jets, because only jets matched to the quarks coming directly from the top quark decay are considered (jets coming from gluon radiation are discarded). Fig. 7 shows differences for light quark corrections in di-jet and $t\bar{t}$ events, and c and b jets have the same behavior but are not shown in the figure. It is not surprising that there are differences given the very different environment of di-jet and $t\bar{t}$ events, including differences in overlapping jets, radiation patterns, renormalization scales, multi-parton interactions, and underlying events. Because of these differences a ”mixed process” closure test clearly fails: when we obtain parton corrections for di-jet events and applied to to $t\bar{t}$ events we do not get a response of 1. On the contrary Fig.8 was obtained using parton corrections derived from $t\bar{t}$ events and then applied to $t\bar{t}$ events, and the closure test works. Similar problems to varying degrees are expected when applying these corrections, either di-jet or $t\bar{t}$, to other processes. In general each time the parton correction is applied, a cross check is needed at least to verify that the closure test is giving the correct result with the particular process under study.

6 Systematic uncertainties

The extraction of the correction function is completely based on Monte Carlo events and the main source of uncertainty is obviously the modeling of the jet formation and evolution. To evaluate the systematic uncertainties, different generator/tuning and ΔR matching parameters were studied and the results compared to the default CMS choice (the Pythia generator with DWT tune and ΔR=0.10).

Fig. 9 shows the systematic effect due to the parton-jet ΔR matching, for gluon jets. Each plotted value is obtained, for each p_T bin, as the mean of the absolute difference for different ΔR parton-jet matching (from 0.05 up to 0.30 with respect to the default 0.10 value) and for the full $|\eta|$ region. Similarly Fig. 10 shows the effect of different generator/tuning obtained comparing the default choice to the three considered options (D6T, S0 and HRW) again on gluon jets. The

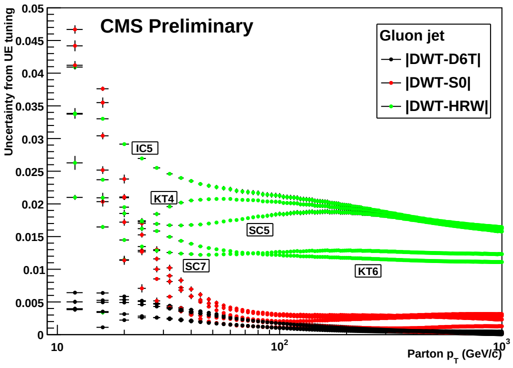

Figure 10: Comparison of the parton-jet response for 3 different generator tunings (D6T, S0 and HRW) with respect to the default CMS choice (DWT): profile histogram of the absolute difference for the full η range. All the 5 jet algorithms are reported (IC5, KT4, KT6, SC5 and SC7) and ΔR=0.10

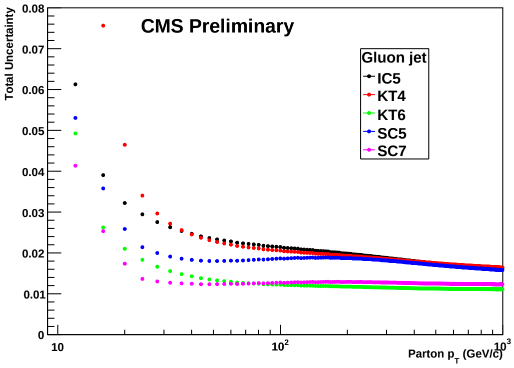

Figure 11: Total uncertainty for different tuning and ΔR combined in quadrature. All the 5 jet algorithms are reported (IC5, KT4, KT6, SC5 and SC7).

biggest effect is observed for the HRW configuration, which sets the uncertainty due to the generator/tuning choice (only for HRW a label is written in the plot to identify the different jet algorithms). Summing in quadrature the two effects, the final systematic uncertainty can be obtained for each flavour and jet algorithm combination as a function of the jet p_T. As an example, the systematic uncertainty associated with the parton level jet correction on gluon jets for p_T^{parton}=20, 100 and 500 GeV/c is reported in Table 6.

	p_T=20 GeV/c			p_T=100 GeV/c			p_T=500 GeV/c		
	ΔR	Tune	Tot	ΔR	Tune	Tot	ΔR	Tune	Tot
IC5	0.014	0.029	0.032	0.0028	0.021	0.021	0.00025	0.017	0.017
KT4	0.041	0.021	0.046	0.0033	0.020	0.020	0.00022	0.017	0.017
KT6	0.008	0.019	0.021	0.0010	0.012	0.012	0.00017	0.011	0.011
SC5	0.015	0.021	0.026	0.0026	0.018	0.018	0.00031	0.017	0.017
SC7	0.002	0.017	0.017	0.0013	0.013	0.013	0.00038	0.012	0.012

Table 1: Systematic uncertainty in jet response of gluons for $p_T^{parton} = 20, 100, 500$ GeV/c and different jet algorithms

7 Conclusions

This note describes the optional parton level jet correction used in CMS. The complete procedure is described in detail for five jet clustering algorithms (IC5, KT4, KT6, SC5 and SC7) and different parameterizations for the jet-parton matching and the tuning of the underlying event simulation. Two equivalent sets of parameters were extracted from QCD di-jet and $t\bar{t}$ events. Correction functions are derived for 5 jet reconstruction algorithms. The corrections are highly flavour dependent, and consequently are derived for gluon jets, light quark jets, c jets, b jets and the all jet mixture for each process. The parton level jet corrections also exhibit process dependent: the corrections derived from di-jet and $t\bar{t}$ events differ by up to 5%.

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